Development of a Regional Coastal and Open Ocean Forecast System

Professor Allan R. Robinson
Division of Engineering and Applied Sciences
Department of Earth and Planetary Sciences
Harvard University
29 Oxford Street
Cambridge, MA 02138-2901
Phone: (617) 495-2819 Fax: (617) 495-5192 Email: robinson@pacific.deas.harvard.edu

Grant #: N000149710239
http://www.deas.harvard.edu/~robinson

LONG-TERM GOALS

The long term goal is to construct, verify and demonstrate an efficient system for the realistic, accurate and efficient estimation of oceanic fields which can be deployed rapidly in any region of the world ocean: the coastal and shelf ocean, across the shelfbreak and the open ocean.

OBJECTIVES

The objectives of this research are:

i) to continue the development of a relocatable, portable and efficient ocean prediction system for real time forecasting and interdisciplinary research;
ii) to implement regional forecast system methodologies;
iii) to demonstrate and validate in real time exercises and predictive skill experiments the Harvard Ocean Prediction System (HOPS) with the Error Subspace Statistical Estimation (ESSE) methodology; and
iv) to share software with the modeling and operational community

APPROACH

Work is ongoing in the areas of:

i) real time autonomous operational methods and protocols, with a focus on objective skill metrics;
ii) advanced techniques for efficient regional prediction, predictability and validation; and
iii) extension and refinements of software

In carrying out continuing research in the three phases (Exploratory, Dynamical, Predictive) of regional forecast system development and the real time forecast process, particular emphasis is now placed on error models, forecasts of error, automated adaptive sampling and automated evaluation of quantitative skill metrics. The approach to software implementation allows for simple and flexible inter-module flow of information and the addition of modules, models and procedures developed in-house or elsewhere. Standard data management procedures, data formats, generic data assimilation

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2003		**00-00-2003 to 00-00-2003**

4. TITLE AND SUBTITLE
Development of a Regional Coastal and Open Ocean Forecast System

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Division of Engineering and Applied Sciences,,Department of Earth and Planetary Sciences,,Harvard University,29 Oxford Street,,Cambridge,,MA, 02138-

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long term goal is to construct, verify and demonstrate an efficient system for the realistic, accurate and efficient estimation of oceanic fields which can be deployed rapidly in any region of the world ocean: the coastal and shelf ocean, across the shelfbreak and the open ocean.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

schemes amenable for use in diverse models are required. The approach to data assimilation emphasizes treatment of the data before assimilation via Structured Data Models (e.g. feature models and Empirical Orthogonal Functions - EOFs) that are used to represent synoptic structures.

WORK COMPLETED

In the past year, HOPS was applied to three real time operational exercises. The first was in collaboration with the Portuguese Hydrographic Institute to predict the currents in the area of the tanker Prestige oil spill during November/December 2002. The second application of HOPS was for the SACLANTCEN MREA03/BP03 exercise that took place in June 2003 in the area near the island of Elba, off the western coast of Italy. Results of the HOPS MREA03/BP03 effort can be found at the web site: http://www.deas.harvard.edu/~leslie/MREA03. A major multi-institutional exercise was the Autonomous Ocean Sampling Network (AOSN-II) experiment that took place in the region off Monterey, CA in July-September 2003. HOPS operational model forecasts, ESSE ensemble forecasts of error fields, adaptive sampling recommendations, and operational presentations can be found at http://www.deas.harvard.edu/~leslie/AOSNII .

HOPS has been utilized to forecast and investigate the synoptic circulation and transports in the Eastern Ligurian Sea [1, 13] and Tunisia-Sardinia-Sicily [5] regions. A first methodology to improve the distribution and management of HOPS computations has been selected, combining run management software (Condor/Sun's GridEngine based on CODINE) within a GRID infrastructure [2]. The HOPS codes and are being distributed to several outside research groups, including MIT scientists as part of the NSF-ITR project "Rapid Real-Time Interdisciplinary Ocean Forecasting: Adaptive Sampling and Adaptive Modeling in a Distributed Environment". The evaluation of the influences of data assimilation, initialization, validation, estimation of parameters, etc. on simulations with coupled physical-biological models has been documented in general [3, 7] and for Massachusetts Bay [4]. Research on the investigation and determination of skill metrics, predictive capabilities and predictability limits was demonstrated in a paper presented at OCEANS02 (Biloxi, MS) in October 2002, "Predictive Skill, Predictive Capability and Predictability in Ocean Forecasting" [6]. HOPS was utilized to investigate coupled physical-biological dynamics in the northeast Atlantic [8]. The cooperative research with the ONR program Capturing Uncertainty in the Common Tactical Environmental Picture effort, Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES) was presented at the 16-20 September 2002 Acoustic Variability meeting in La Spezia, Italy [9, 10]. Feature models for the circulation of the Gulf of Maine have been developed and documented [11, 12]. The concept of interdisciplinary ocean prediction systems with coupled data assimilation was presented [14, 15]. The Multi-Scale Energy and Vorticity Analysis (MS-EVA) methodology has been completed and applied to basic instability processes [18, 19] and a realistic study of the Iceland-Faeroe Front [20]. The MS-EVA approach is being applied to determine the dynamical evolution of the upwelling-relaxation phases of the Monterey Bay coastal upwelling.

Additional information on the work accomplished for this project is available via the principal investigator's web site: http://www.deas.harvard.edu/~robinson and the associate investigator’s web site at: http://www.deas.harvard.edu/~pierrel.

RESULTS

Real-time Exercises

The Harvard Ocean Prediction System was put to use during the past year in three major exercises. The first took place in response to the sinking of the oil tanker Prestige off the coast of Portugal in November 2002. HOPS, in collaboration with the Portuguese Hydrographic Institute, predicted the evolution of currents and patterns of possible oil spill movements for guidance regarding collection efforts during November/December 2002. Additional collaborations relating to this incident were with the NOAA Hazardous Materials Response, SACLANTCEN, and the University of Vigo, among others. The SACLANTCEN MREA03/BP03 exercise took place in June 2003 in the area near the island of Elba, off the western coast of Italy. During this exercise HOPS provided real-time forecasts during the 11-17 June time period. A new concept to investigate sub-mesoscale real-time modeling, known as Mini-HOPS, was introduced during MREA03/BP03. A set of nested domains was designed which are observable in an inertial time period. Data was used for small domain real-time assimilation in order to evaluate the capability of resolving higher frequency sub-mesoscale/inertial dynamics. Knowledge and experience gained will be used to design a strategy that will allow for the reduction of uncertainty of operational models in very dynamic areas, where the uncertainty can be expected to be very high.

The third, and most comprehensive operational exercise was the multi-institutional Autonomous Ocean Sampling Network (AOSN-II) experiment that took place in the region off Monterey, CA in July-September 2003. The AOSN-II 2003 Monterey Bay Field Experiment brought together physical oceanographers, AUV engineers, marine biologists and dynamical modelers. This diverse group studied Monterey Bay using dynamical ocean circulation models and observational tools such as satellites, airplanes, ships, drifters, buoys, autonomous underwater vehicles, and an entire fleet of undersea gliders. The researchers used these tools to observe and predict the upwelling and movement of cold, nutrient-rich water that occurs off Monterey Bay during the summer months. These upwelling events create blooms of marine plankton that support the abundant fisheries and other wildlife in and around the bay. During AOSN-II, the Harvard HOPS team achieved: 23 sets of real-time nowcasts and forecasts of temperature, salinity and velocity were released between 4 August and 3 September; 10 sets of real-time ESSE forecasts, comprised of a total of 4323 ensemble members, were issued over the same time period: adaptive sampling recommendations for ship and glider observations were suggested on a routine basis; a web site (http://www.deas.harvard.edu/~leslie/AOSNII/index.html) was developed for daily distribution of forecasts, scientific analyses, data analyses, special products and control-room presentations; and, data from ships (Pt. Sur, Martin, Pt. Lobos), gliders (WHOI and Scripps) and aircraft SST were assimilated within 24 hours of their appearance on the data server. Adaptive sampling was carried out on two time scales: i) HOPS /ROMS produced two-day forecasts of important dynamical events (hot spots) which were identified for investigation; and, ii) ESSE error forecasts were analyzed to identify errors where observations would reduce model errors. A novel aspect of this approach was to use a “sub-optimal” trial assimilation of such sampled data to investigation its *a priori* effects.

The concepts involved in the evaluation and quantitative verification of ocean forecasts and two predictive skill experiments to develop and research these concepts, carried out in the North Atlantic and Mediterranean Sea in 2001 and 2002 are described in [6]. An initial set of objective skill metrics, root-mean-square error and pattern correlation coefficient, have been used to assess the real-time skill

of HOPS during the Assessment of Skill for Coastal Ocean Transients (ASCOT) project. ASCOT is a series of real-time experiments and simulations focused on quantitative skill evaluation, carried out by the Harvard Ocean Prediction System group in collaboration with the NATO SACLANTCEN. ASCOT-01 was carried out in Massachusetts Bay and the Gulf of Maine in June 2001. ASCOT-02 took place in May 2002 in the Corsican Channel near the island of Elba in the Mediterranean Sea. Results from the ASCOT exercises highlight the dual use of data for skill evaluation and assimilation, real-time adaptive sampling and skill optimization and quantitatively demonstrate both real-time and *a posteriori* evaluations of predictive skill and predictive capability.

General Results

ESSE has been shown to be useful for a wide range of purposes as illustrated by three particular investigations [7]. The smoothing estimation of physical ocean fields in the Eastern Mediterranean provided dynamically consistent fields superior to those obtained by statistical methods alone. The coupled physical-acoustical data assimilation in the Middle Atlantic Bight shelfbreak demonstrated the multi-scale nature of ESSE in recovering the fine scale transmission loss signal from coarser resolution data and physical ocean model. The impacts of interdisciplinary ESSE filtering and smoothing were quantified in coupled physical-biological dynamical simulations for Massachusetts Bay. The ESSE estimates provided evidence of patchiness in the Chl-a field and highlighted the effects of storms, of sub-mesoscale to mesoscale variability and of decreasing light levels on the Chl-a field at the end of the 1998 summer. The uncertainties in the predicted acoustic wavefield associated with the transmission of low-frequency sound from the continental slope, through the shelfbreak front, onto the continental shelf have been examined in [10]. The combined ocean and acoustic results from the simulation study provides insights into the relations between the uncertainties in the ocean and acoustic estimates [17, 18].

A generalized approach to feature-oriented regional modeling for various types of fronts is presented in [12]. Large-scale meandering frontal systems such as the Gulf Stream, Kuroshio, etc. can be modeled via velocity-based feature models, while buoyancy forced coastal water mass fronts such as coastal currents, tidal fronts, etc. can be modeled by a generalized parameterized water mass feature model. The multi-scale synoptic circulation systems in the Gulf of Maine and Georges Bank region are summarized using a feature-oriented approach in [13]. A synoptic initialization scheme for feature-oriented regional modeling and simulation of the buoyancy-driven circulation in the coastal-to-deep region has been developed. The applicability of feature-oriented regional modeling and simulation for multi-scale, multi-domain, and multi-disciplinary nested forecast systems has been demonstrated.

The Multi-Scale Energy and Vorticity Analysis (MS-EVA) methodology [18, 19] has been developed to investigate sub-mesoscale, mesoscale, and large-scale dynamical interactions in oceanic free jets. MS-EVA is based on a multi-scale window transform (MWT), which is a local, orthonormal, and self-similar functional analysis tool that is windowed on scales, with location resolution maximized in the phase space. As a real ocean application, the MS-EVA has been used to diagnose the dynamics of the Iceland-Faeroe Front (IFF) [20]. The calculated energetics, when locally averaged, reveal that the formation of the observed mesoscale meander is a result of both a baroclinic instability and a barotropic instability, with the former dominant in the western region at mid-depths, while the latter is more active in surface layers. A preliminary MS-EVA analysis has been performed on the AOSN-II simulation that begins August 21. At the beginning of the simulation, there is a steady transfer of

potential energy at 500m from the large-scale time window (longer than 10 days) to the meso-scale window (2 to 10 days) in Monterey Bay, and a steady transfer of kinetic energy just outside the bay. No significant local increases of meso-scale potential energy and kinetic energy have been identified at the corresponding locations.

A generalized, flexible biological model, suitable for adaptive modeling is being developed and an *a priori* set of parameterizations has been determined with various adaptive options. The model consists of 7 functional groups of state variables: nutrients (N_i), phytoplankton (P_i), zooplankton (Z_i), detritus (D_i), dissolved organic matter (DOM_i), bacteria (B_i) and auxiliary state variables (A_i). Primarily, DOM are classified by their chemical composition, bacteria by their ability in response to environmental variations, nutrients by their chemical composition and phytoplankton, zooplankton and detritus by their size, respectively. Different classification can be used, however, such as species and stages of zooplankton development. Auxiliary state variables represent oceanic properties that are not independent components in the food web structure and trophic dynamics, but their fields usually depend on other biological features (e.g. chlorophyll, bioluminescence, optics, dissolved oxygen, CO_2, etc). The model can be adaptive, i.e. the state variables, model structures and parameter values can change in response to field measurements, ecosystem function and scientific objectives. This generalized biological model has been coupled with HOPS. Tests of functionality and reliability are underway in Massachusetts Bay and Monterey Bay. The generality, flexibility and adaptability of the generalized biological model will enable significant progress in adaptive modeling and real-time forecasting of marine ecosystems.

IMPACT/APPLICATIONS

The HOPS/ESSE concept of Ocean Observing and Prediction Systems for contemporary ocean science and marine technology consist is that of: i) a set of coupled interdisciplinary models; ii) an observational network with multiple platforms and sensors; and, iii) data assimilation schemes with measurement models and error models. This was importantly demonstrated in a powerful way by the demonstration of concept AOSN-II exercise carried out in this time period. The nowcasts, forecasts and data driven simulation products of Ocean Observing and Prediction Systems have important applications for: i) the efficient conduct of real time scientific research in the intermittent ocean; ii) marine resource exploration, exploitation and management; and, iii) naval and marine operations.

TRANSITIONS

Completed and continuing research transitions and collaborations include: MIT Ocean Engineering, MIT Sea Grant; Southampton Oceanography Center; NRL Stennis; Naval Postgraduate School; SACLANT Undersea Research Centre; WHOI; SIO; JPL Pasadena; Old Dominion University; Institute of Marine Sciences, Turkey; U. Tokyo; CNR Ancona, Italy; U.Cal. - Santa Cruz; and U. Mass. Dartmouth. The integration of HOPS into the AOSN system has been initiated with the August 2003 experiment and will be furthered by OSSES to be carried out in 2003-2004. The ESSE methodologies and codes continue to be transferred to ROMS-TOMS in collaboration with Rutgers Univ.

RELATED PROJECTS

The collaborations with the SACLANT Undersea Research Centre's Oceanography Group are evidenced by the recent MREA03/BP03 exercise. This project is related to: Harvard 6.1 research ("Dynamics of Oceanic Motions"); Harvard Uncertainty research ("Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture"), an NSF-OIT project "Rapid Real Time Interdisciplinary Ocean Forecasting Adaptive Sampling and Adaptive Modeling in a Distributed Environment" (Prof. N. Patrikalakis and Prof. H. Schmidt - MIT; Prof. J.J. McCarthy - Harvard) as well as external collaborations in conjunction with transitions.

PUBLICATIONS

[1] Robinson, A.R., J. Sellschopp, W.G. Leslie, R. Onken, A. Alvarez, G. Baldasserini, P.J. Haley, Jr., P.F.J. Lermusiaux, C. Lozano, E. Nacini, R. Stoner and P. Zanasca (2003) Real-Time Forecasting of Synoptic Transients in the Eastern Ligurian Sea. Bovio, E., R. Tyce and H. Schmidt (Editors), Autonomous underwater vehicle and ocean modeling networks: GOATS 2000. Proceedings of a conference held in La Spezia, Italy, NATO SACLANT Undersea Research Centre, *SACLANTCEN Conference Proceedings Series* CP-46.

[2] Evangelinos, C., R. Chang, P.F.J. Lermusiaux and N.M. Patrikalakis (2003) Rapid real-time interdisciplinary ocean forecasting using adaptive sampling and adaptive modeling and legacy codes: Component encapsulation using XML. *Proceedings of Computational Science - ICCS 2003*, International Conference on Computational Science 2003, Saint Petersburg, Russian Federation, and Melbourne, Australia, June 2003, P.M.A. Sloot, D. Abramson, A. Bogdanov, J.J. Dongarra, A. Zomaya and Y. Gorbachev (Editors). Lecture Notes in Computer Science, Springer, **2660**, 375-384.

[3] Gregoire, M., P. Brasseur and P.F.J. Lermusiaux (Guest Editors) (2003) The use of data assimilation in coupled hydrodynamic, ecological and bio-geo-chemical models of the ocean. Special Issue, 33rd International Liege colloquium, May 2001. *Journal of Marine Systems*, **40**, 1-3.

[4] Besiktepe, S.T., P.F.J. Lermusiaux and A.R. Robinson (2003) Coupled physical and biological data driven simulations of Massachusetts Bay in late summer: Real-time and post-cruise data assimilation. Special Issue on "The use of data assimilation in coupled hydrodynamic, ecological and bio-geo-chemical models of the oceans," Gregoire M., P. Brasseur and P.F.J. Lermusiaux (Editors), *Journal of Marine Systems*, **40**, 171-212.

[5] Onken, R., A.R. Robinson, P.F.J. Lermusiaux, P.J. Haley, Jr., and L.A. Anderson (2003) Data-driven Simulations of Synoptic Circulation and Transports in the Tunisian-Sardinia-Sicily Region. *Journal of Geophysical Research*, **108** (C9), 8123-8135.

[6] Robinson, A.R., P.F.J. Lermusiaux, P.J. Haley, Jr. and W.G. Leslie (2002) Predictive Skill, Predictive Capability and Predictability in Ocean Forecasting. *Proceedings of* Oceans *2002 IEEE/MITS Conference*, 787-794.

[7] Lermusiaux, P.F.J., A.R. Robinson, P.J. Haley, Jr. and W.G. Leslie (2002) Advanced Interdisciplinary Data Assimilation: Filtering and Smoothing via Error Subspace Statistical Estimation. *Proceedings of Oceans 2002 IEEE/MITS Conference*, 795-802.

[8] Popova, E.E., C.J. Lozano, M.A. Srokosz, M.J.R. Fasham, P.J. Haley, Jr. and A.R. Robinson (2002) Coupled 3D Physical and Biological Modelling of the Mesoscale Variability Observed in North-East Atlantic in Spring 1997:Biological Processes. *Deep-Sea Research Part I: Oceanographic Research*, **49**(10) 1741-1768.

[9] Robinson, A.R., P. Abbot, P.F.J. Lermusiaux and L. Dillman (2002) Transfer of uncertainties through physical-acoustical-sonar end-to-end systems: A conceptual basis. *Acoustic Variability 2002*. N.G. Pace and F.B. Jensen (Editors), SACLANTCEN. Kluwer Academic Press, 603-610.

[10] Lermusiaux, P.F.J. and C.-S. Chiu (2002) Four-dimensional data assimilation for coupled physical-acoustical fields. *Acoustic Variability, 2002*. N.G. Pace and F.B. Jenson (Editors), SACLANTCEN. Kluwer Academic Press 417-424.

[11] Gangopadhyay, A. and A.R. Robinson (2002) Feature-Oriented Regional Modeling of Oceanic Fronts. *Dynamics of Atmospheres and Oceans*, **36**, 201-232.

[12] Gangopadhyay, A., A.R. Robinson, P.J. Haley, Jr., W.G. Leslie, C.J. Lozano ,J.J. Bisagni and Z. Yu (2003) Feature Oriented Regional Modeling and Simulations (FORMS) in the Gulf of Maine and Georges Bank. *Continental Shelf Research*, **23** (3-4), 317-353.

PUBLICATIONS (IN PRESS AND SUBMITTED)

[13] Onken, R., A.R. Robinson, L. Kantha, C.J. Lozano, P.J. Haley and S. Caniel (2003) A Rapid Response Nowcast/Forecast System Using Multiply-Nested Ocean Models and Distributed Data Systems. *Journal of Marine Systems.* [In press]

[14] Robinson, A.R. and W.G. Leslie (2003) Advanced Systems for Operational Ocean Forecasting of Interdisciplinary Fields and Uncertainties. Proceedings of the MREP2003 Conference (R. Tyce, editor), SACLANTCEN. [In press]

[15] Robinson, A.R. and P.F.J. Lermusiaux (2003) Prediction Systems with Data Assimilation for Coupled Ocean Science and Ocean Acoustics. Proceedings of the Sixth International Conference on Theoretical and Computational Acoustics (A. Tolstoy, et al., editors), World Scientific Publishing. [In press]

[16] Sundermeyer, M.A., B.J. Rothschild and A.R. Robinson (2003) Environmental indicators and the predictability of commercial fish stocks, Part II: Evaluation using spacially explicit models. *Fisheries Oceanography*. [In press]

[17] Sundermeyer, M.A., B.J. Rothschild and A.R. Robinson (2003) Environmental indicators and the predictability of commercial fish stocks, Part I: An empirical approach using commercial landing data. *Fisheries Oceanography*. [In press]

[18] Liang, X.S., and A.R. Robinson (2003) Localized Multiscale Energy and Vorticity Analysis: I. Fundamentals. *Dynamics of Atmospheres and Oceans.* [Submitted]

[19] Liang, X.S., and A.R. Robinson (2003) Localized Multiscale Energy and Vorticity Analysis: II. Instability theory and validation. *Dynamics of Atmospheres and Oceans.* [Submitted]

[20] Liang, X.S., and A.R. Robinson (2003) A study of the Iceland-Faeroe Frontal variability with the Multiscale Energy and Vorticity Analysis. *Journal of Physical Oceanography.* [Submitted]